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Planetary and Space Science 52 (2004) 587–590
Planetary and Space Science
www.elsevier.com/locate/pss

Deflection of near-Earth asteroids by kinetic energy impacts from retrograde orbits

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Received 20 August 2003; received in revised form 3 December 2003; accepted 5 December 2003

Abstract

Previous studies of non-nuclear diversion of near Earth asteroids have largely ignored the use of pure kinetic energy impacts, partly due to apparent limits on impact speeds of 10–15 km s^{-1}. Here, I will consider the use of a near-term solar sail to deliver an inert projectile onto a retrograde solar orbit, thus raising impact speeds to at least 60 km s^{-1}. Such high-energy orbits increase the energy liberated during impact by a factor of 40 or more, while reducing the required projectile mass by at least 95%. This considerable reduction in projectile mass allows kilometre-sized asteroids to be diverted with current launch vehicles, near-term technologies and at a cost comparable to a modest deep space mission.

Keywords: Near Earth asteroids; Non-nuclear deflection; Solar sailing; Orbital mechanics

1. Introduction

Many authors have documented the potential terrestrial hazard posed by the impact of near Earth asteroids (Alvarez et al., 1980; Chapman and Morrison, 1994; Binzel, 2000; Rabinowitz et al., 2000). While current efforts are focused on detecting and cataloguing such objects, several schemes for hazard mitigation have been both proposed and investigated in some detail (Ahrens and Harris, 1992; Melosh, 1993; Melosh et al., 1994; Spitale, 2002). Although nuclear devices appear attractive for deflecting potentially hazardous near Earth asteroids (Ahrens and Harris, 1992), serious political issues arise concerning the deployment of nuclear weapons in space (Sagan and Ostro, 1994). In order to overcome such difficulties, non-nuclear options have been proposed, such as focusing solar radiation onto the target asteroid with a large collector and smaller steerable secondary mirror to generate a hot jet of exhaust gas (Melosh, 1993; Melosh et al., 1994). Other schemes consider coating the asteroid to alter its albedo, and hence modify the Yarkovsky induced acceleration (Spitale, 2002). However, solar concentrators require reaction propulsion to offset the solar radiation pressure acting on the collector, while the secondary mirror could experience serious degradation over time, due to hot ejecta from the asteroid surface. Indeed, since it can be shown that the secondary mirror must subtend a solid angle of at least 0.05 sr (Melosh et al., 1994) at the heated spot, the secondary mirror will experience a thrust of order 10^{-2} of that experienced by the asteroid itself, assuming hemispherical ejection of material. This large continuous thrust must then be countered over the operating period of the deflection system in order to station-keep the secondary mirror at the focus of the main collector. Similarly, to coat a kilometre sized body to a depth of 0.1 cm to modify its albedo (Spitale, 2002) would require a mass of up to 2.5×10^7 kg, which does not appear attractive compared to other non-nuclear schemes. It should be noted however, that due to the wide range of asteroid physical properties and orbital elements, and the likely range of interior structures, a corresponding range of hazard mitigation techniques may be required, each of which may be suited to a different mitigation scenario.

Nuclear deflection requires a stand-off detonation, where a nuclear device is used to heat the surface layer of the asteroid through the conversion of neutrons and X-rays into thermal energy, inducing a perturbation to the asteroid orbit through the momentum transported away by the blown-off surface material (Ahrens and Harris, 1992). While the specific yield of nuclear explosives is great ($\sim 1 \times 10^{12}$ J kg^{-1} for a complete fusion device) (Remo, 2000), the coupling of liberated energy to the asteroid may be low. For exam-

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doi:10.1016/j.pss.2003.12.010

ple, the conversion efficiency of liberated energy into heat at the asteroid surface may be as low as 0.03 (Ahrens and Harris, 1992), while at an optimum stand-off distance the geometric efficiency is of order 0.3, resulting in a worst case effective yield of order 9×10^9 J kg^{-1}. For a pure kinetic energy projectile impinging with a relative speed of order 10 km s^{-1}, the specific energy is of order 5×10^7 J kg^{-1} (conventional explosives deliver $\sim 4 \times 10^6$ J kg^{-1}), while the yield can be raised to $\sim 2 \times 10^9$ J kg^{-1} for a 60 km s^{-1} projectile. Such an impact speed is characteristic of a projectile delivered to a retrograde orbit, assuming the asteroid orbit is near circular at 1 astronomical unit (AU).

2. Kinetic energy deflection

The required change in speed Δv to be delivered to the asteroid in order to induce a change in position of 1 Earth radius can be determined as a function of the time to impact t. From the orbital mechanics of the problem it can be shown that a simple scaling law applies such that $\Delta v(\mathrm{m\ s^{-1}}) \sim 0.07/t(\mathrm{yr})$ (Ahrens and Harris, 1992). Therefore, an impulse of order 1 cm s^{-1} is required for a typical lead-time of order 10 years. This is the time at which the impulse is applied prior to impact, and does not account for the time required to deliver the nuclear device, projectile or other system to the asteroid. Since many near Earth asteroids are in extremely high-energy orbits, this time could be substantial for delivery by conventional means. For a pure kinetic energy impact, Melosh et al. (1994) determines the diameter d of asteroid which can be diverted with a lead time t through the impact of a body of diameter L with impact speed v through the use of semi-empirical cratering laws as $d(\mathrm{km}) = 0.14L(\mathrm{m})^{0.81}t(\mathrm{yr})^{0.27}v(\mathrm{km\ s^{-1}})^{0.46}$. The cratering law is that of Schmidt and Housen (1987), which is a function of the Froude number of the target body and the length scale of the impactor. Other related impact models (Ahrens and Harris, 1994) have been used elsewhere, however the analysis of Melosh is adopted here to allow direct comparison with his results. Clearly, the scaling laws for impactor sizing are sensitive to the underlying assumptions used. Assuming zero mechanical strength, the minimum diameter body which can be considered before fragmentation is likely is estimated to be $d_{\mathrm{min}}(\mathrm{km}) = 0.7(L(\mathrm{m})^2 v(\mathrm{km\ s^{-1}})/\sqrt{G\rho(\mathrm{kg\ m^{-3}})})^{1/3}$, where G is the universal gravitational constant and ρ is the asteroid density, assumed to be of order 3000 kg m^{-3}.

The utility of high-speed projectiles can be seen from Fig. 1, which shows the effect of raising the projectile impact speed from 10 to 60 km s^{-1}. It can be seen that a relatively modest projectile can now be used to divert kilometre-sized asteroids, given sufficient lead-time. For example, to divert a 2 km asteroid with a 10 year lead-time requires a 10 km s^{-1} projectile with a diameter of order 3.3 m and a mass of order 60 tons, assuming a projectile density similar to that of the asteroid. This is greater than the Earth escape capacity of any operational launch vehicle. Using a retrograde orbit, and so raising the impact speed to 60 km s^{-1}, leads to a significant reduction in the projectile mass to only 2.8 tons, some 5% of that required for a slower impact.

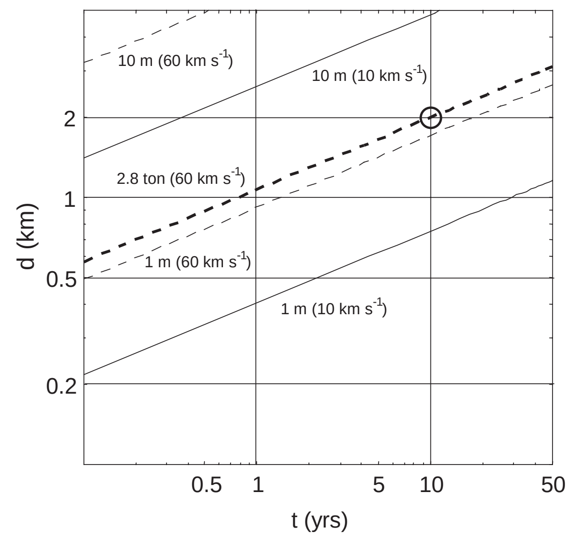

Fig. 1. Deflection capability of kinetic energy impacts on targets bodies from prograde (10 km s^{-1}) and retrograde (60 km s^{-1}) orbits. The bold line indicates a 2.8 ton (1.2 m) projectile which is sized to divert a 2 km body with a 10 year lead time (marked—o). Such a task would require a 60 ton (3.3 m) projectile if a prograde impact at 10 km s^{-1} is assumed. The retrograde impact therefore leads to a significant reduction in the projectile mass of order 95%.

The minimum asteroid diameter to avoid disruption, assuming zero mechanical strength, is estimated to be of order 0.4 km, so that a 60 km s^{-1} impact of a relatively small 1.2 m projectile on a 2 km body appears to be a reasonable proposition. However, detailed modelling of such impacts is required, since the effectiveness of the impact is strongly dependent on the internal structure of the target body (Asphaug et al., 1998). If fragmentation were deemed a significant risk, a retrograde orbit matching a target body near 1 AU could be used to deliver a small projectile every 6 months. Alternatively, if multiple projectiles are released with a relative to speed of order 1 m s^{-1}, 6 months prior to closest approach, a series of small impacts could be delivered, with the impacts spread over a 15 min interval.

It is of interest to note that Ahrens and Harris (1992) estimate a (worst case) requirement for a 0.1 Megaton nuclear device to divert a 1 km asteroid with a 10 year lead time. Assuming 4 kg per Kiloton yield (Remo, 2000), the mass of the nuclear device is of order 0.5 ton, which is approaching the 2.8 ton inert mass required for a retrograde impact. While the nuclear option is clearly attractive in terms of mass efficiency, a retrograde impact (or multiple impacts) from an inert mass of not too dissimilar size appears to be able to perform the same function, but without the political difficulties posed by deploying nuclear weapons in space (Sagan and Ostro, 1994). Other options, such as using extremely efficient reaction propulsion (such as nuclear electric propulsion) with a specific impulse of order 9000 s requires a reaction mass of order 10^3 ton.

3. Projectile delivery

Delivering a payload with a mass of several tons to such a high-energy retrograde orbit is a truly daunting prospect for conventional propulsion systems. For example, to deliver the 2.8 ton projectile to a retrograde orbit at 1 AU from Earth escape requires a Δv of order 60 km s^{-1}. Using chemical propulsion with a specific impulse I_{sp} of 450 s (space shuttle main engines), leads to an initial mass of order 2×10^6 tons. The use of high-efficiency solar electric propulsion (I_{sp} of 3000 s) still leads to a minimum initial mass of order 22 tons, neglecting trajectory gravity losses and the dry mass of the propulsion system. A more attractive form of low thrust propulsion for such exceptionally high-energy missions is solar sailing (McInnes, 1999). Solar sails use the ambient flux of momentum transported by solar photons, and so crucially are not constrained by reaction mass. The component technologies for solar sailing have been greatly advanced in recent years, with near-term concepts (Murphy et al., 2002) providing a sail assembly loading σ (ratio of sail film and structural mass to sail area) of order 5 g m^{-2}. The characteristic acceleration a_c of a solar sail is defined as the acceleration experienced at 1 AU and can be written as $a_c = 2P/(\sigma + m_p/A)$, where P (4.56×10^{-6} N m^{-2}) is the solar radiation pressure experienced at 1 AU, m_p is the payload mass and A the sail area, while the factor 2 assumes a perfectly reflecting sail (McInnes, 1999).

A solar sail can deliver payloads into high-energy retrograde orbits using tricks of orbital mechanics which are unique to solar sailing (McInnes, 1999). In order to increase the available solar radiation pressure, the solar sail spirals inwards from 1 AU to a close solar orbit, typically at 0.25 AU, requiring approximately 2.5 years for a typical solar sail characteristic acceleration of 0.3 mm s^{-2}. At the 0.25 AU orbit, the sail is then pitched such that a component of the thrust vector is directed alternately above and below the instantaneous orbit plane every half orbit. This ‘orbit cranking’ manoeuvre (Fig. 2) increases the solar sail orbit inclination Δi in a monotonic fashion, where it can be shown (McInnes, 1999) that $\Delta i(\deg) \sim 15R(\mathrm{AU})^{-1.5} a_c(\mathrm{mm\ s^{-2}}) \Delta t(\mathrm{yr})$ for a cranking orbit radius R. For a characteristic acceleration of 0.3 mm s^{-2} the time to rotate the orbit plane through 180° into a retrograde orbit is of order 5 years, assuming the target body is in the ecliptic plane. From this retrograde orbit at 0.25 AU, the solar sail then follows a minimum-time trajectory to the target asteroid. For a target orbit close to 1 AU a further 2.5 years is therefore required, resulting in a total trip time from Earth escape to a near 1 AU retrograde orbit of order 10 years. Somewhat higher performance solar sails with characteristic accelerations of 0.5–1 mm s^{-2} can deliver the projectile in 6.2–3.9 years, respectively.

For a target in a near circular orbit at 1 AU the relative speed of the solar sail and asteroid is the twice the circular orbit speed at 1 AU, so that the impact speed is of order 60 km s^{-1}, as assumed earlier, delivering an energy yield equivalent to a 1.25 Megaton nuclear device. Since the most likely impacting orbit is from a body with a perihelion not far inside the Earth’s orbit, this represents a useful scenario to consider. It should be noted that this is the minimum retrograde impact speed that can be expected for a potentially hazardous asteroid. For asteroids with a significant orbit eccentricity substantially higher impact speeds can be expected. An asteroid with a perihelion at 0.25 AU and a large aphelion could yield an impact speed of up to 140 km s^{-1}, assuming that the projectile is delivered at perihelion. Using the scaling law detailed above, a 2 km body could be diverted with a projectile mass of order 650 kg. Even for low eccentricity target bodies, the impact(s) should occur at perihelion in order to maximise the impact speed.

4. Discussion

For a solar sail characteristic acceleration of order 0.3 mm s^{-2} and a sail assembly loading of 5 g m^{-2}, a square solar sail with a side of 330 m is required, which is within the scale currently being considered for future mission applications (Murphy et al., 2002). The mass of the solar sail assembly is then 550 kg, resulting in a launch mass of order 3350 kg, which can be delivered to an Earth escape trajectory by a Zenit-3SL launch vehicle. The launch costs are of order \$90M (FY03), while the cost of the solar sail can be estimated at \$60M. Additional costs of order \$150M are required for the spacecraft bus and targeting system for the terminal approach to the asteroid. The NASA Deep Impact mission will deliver a 370 kg projectile to comet Tempel-1 at 10 km s^{-1}, so targeting systems are well developed at somewhat lower speeds but would clearly be difficult at $\sim$ 60 km s^{-1}. It is therefore estimated that a 2 km asteroid could be diverted using a high-energy retrograde impact at an approximate cost of \$300M. If the solar sail characteristic acceleration is raised to 1 mm s^{-2}, the trip time to a retrograde 1 year orbit falls to only 3.9 years as noted above, requiring an 820 m sail with a total launch mass of 6150 kg, suitable for launch to Earth escape on a Titan IV launch vehicle. For a smaller target body with a diameter of 0.5 km, a 165 kg projectile is required for a lead-time of 1 year requiring a 200 m sail, again for a characteristic acceleration of 1 mm s^{-2} (3.9 year trip time), resulting in a launch mass of only 360 kg.

In summary, small kinetic energy projectiles can be an attractive option for diverting potentially hazardous near Earth asteroids, if the impact speed is sufficiently high. The use of a relatively modest solar sail to efficiently deliver a projectile onto a high-energy retrograde orbit can enable such a scheme to be considered in the near-term. While other non-nuclear schemes require significant technology development, solar sailing is approaching flight readiness, allowing kilometre-sized asteroids to be diverted with a launch mass compatible with current medium-sized launch vehicles.

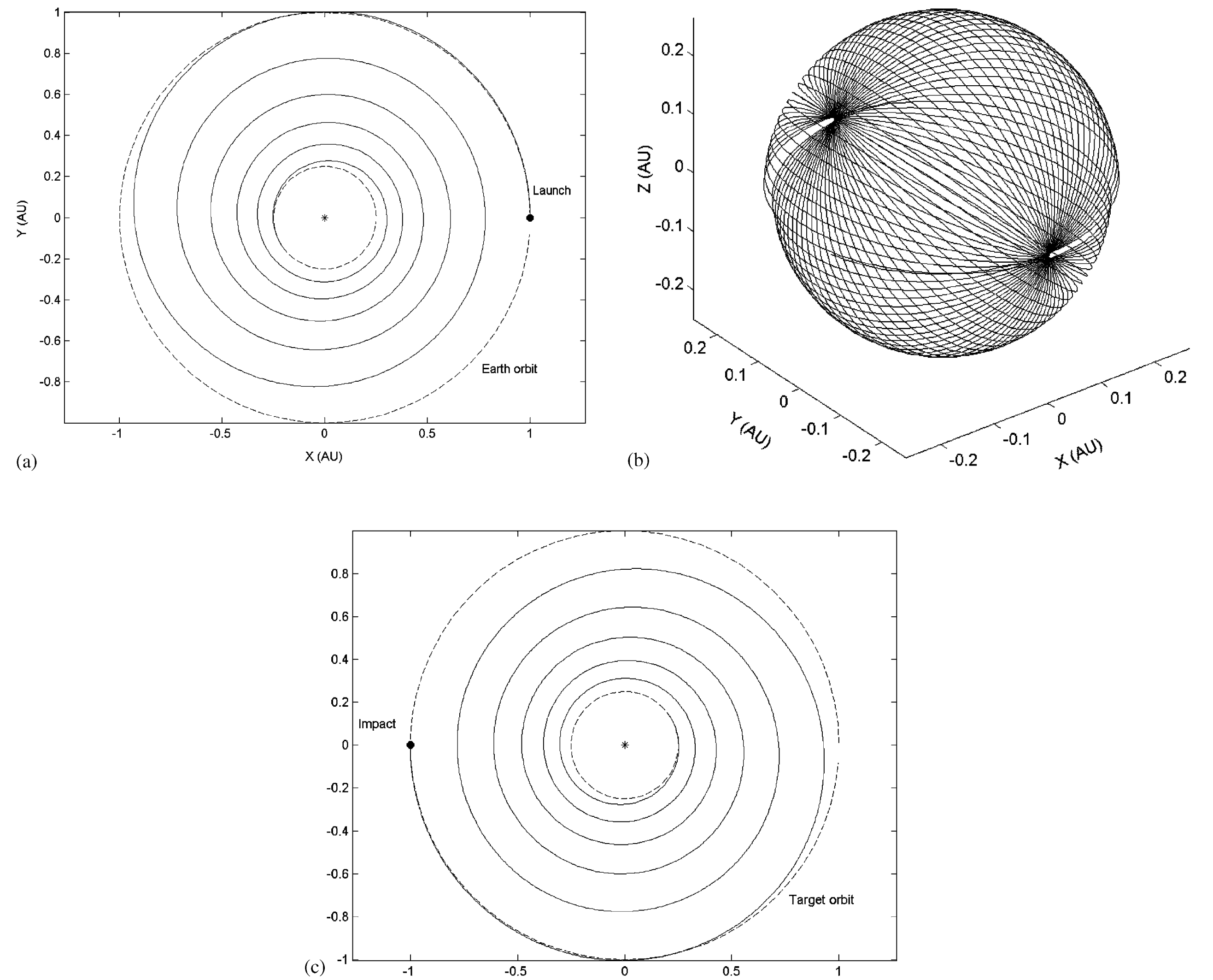

Fig. 2. Solar sail transfer to a retrograde orbit (characteristic acceleration of 0.3 mm s^{-2}) (a) The solar sail spirals to a close, thermally limited, solar orbit at 0.25 AU and then (b) follows an inclination cranking phase to reach a retrograde orbit within the orbit plane of the target body. (c) From there, the solar sail spirals outwards to reach the target body (assumed at 1 AU) on a retrograde orbit and to target and release the kinetic energy projectile.

Acknowledgements

This work was support by the Leverhulme Trust.

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